Hydraulic Transients used for Leakage Detection in Water Distribution Systems

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ABSTRACT

The current paper focuses on leakage detection and location in pipe networks based on a recent and novel approach, known as inverse transient analysis. The main idea behind this methodology is the identification of leaks location in pipe networks using observed pressure data, collected during the occurrence of transient events, and the minimisation of the difference between observed and calculated parameters. This approach is presented conceptually and implemented in a software tool. The methodology is tested and verified with laboratory data collected in an experimental facility at Instituto Superior Técnico (Technical University of Lisbon). Based on this preliminary data analysis, the main practical difficulties of the implementation of this methodology in field network systems are outlined.

1 INTRODUCTION

In the last decade, the changing climatic conditions, in which the extreme events of floods and droughts have been increasingly more frequent, have led to water shortages in many countries of the world. Furthermore, it is well known the importance of water losses in the overall total distributed water. According to a study carried out in 31 water distribution companies in the UK published in **WRc (1994)**, almost 50% of water is unmeasured but consumed, 25% measured and consumed, and almost 23% is lost in leaks and ruptures in the network (**Figure 1**). Consequently, water companies have started to concentrate their efforts on a better management of the water distribution systems that go from the implementation of leakage reduction and control policies to the demand management strategies.

This paper aims to present a novel leakage detection methodology – inverse transient analysis – developed, not to substitute the existing leakage techniques and equipment, but as alternative method to help engineers on the hard task of leakage detection and location. This methodology is based on pressure data collection during the occurrence of transient events and the minimisation of the difference between observed data and calculated pressures (or flows). This procedure is essentially an optimisation problem that systematically calls a hydraulic transient simulator to evaluate system's behaviour under the certain conditions.

The paper is organised in four main parts. In the first part, the concept of the inverse transient analysis is presented and the methodology implementation, which presupposes the development of a software tool, is explained. Secondly, an experimental facility assembled at

Instituto Superior Técnico (Technical University of Lisbon) to validate this methodology is described and the collected data under perfectly controlled laboratory conditions is assessed and compared with transient simulation results. In the third part, the implemented inverse transient tool is tested with the collected transient data and an example of leakage detection is presented. At last, conclusions are drawn about the possible future application of this method in real systems.

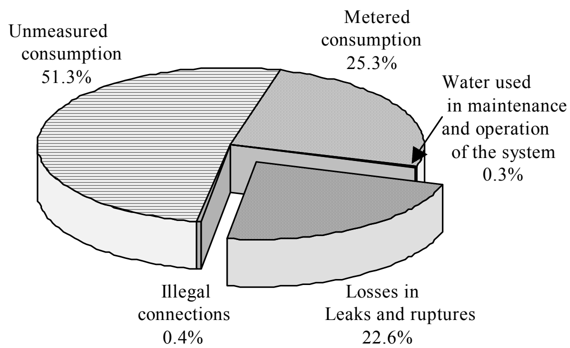

Figure 1 - Water volume distributed and lost in the pipe network (WRc Report B, 1994)

2 INVERSE TRANSIENT METHOD

2.1 Background review

The current research focuses on leakage detection in water distribution systems by means of the inverse transient method. This method consists of the identification of the unknown parameters - leaks locations - using observed transient data. The parameter identification is an optimisation problem in which the system's behaviour is simulated by a hydraulic model and the difference between observed and calculated variables is minimized by an optimisation model.

This inverse transient analysis is a relatively new approach combining the inverse method with the transient analysis in networks. **Pudar & Liggett (1992**) have theoretically elaborated the inverse method for leakage detection applied to steady state only. The inverse steady-state analysis for leakage detection is theoretically an elegant technique, however, it has the drawback of needing the accurate knowledge of the friction factors in all pipes in order to have confidence on the results of leaks' locations. Moreover, a true steady state hardly exists in real networks, which makes the steady state analysis inadequate for a continuous monitoring of the system.

Liggett & Chen (1994, 1995) have extended the methodology to transient events. The inverse transient analysis has proved, at least numerically, to have the capability of simultaneous leaks detection and network calibration. In fact, pressure waves are less affected by pipe frictions, almost eliminating the dependence of the leakage detection success, on pipe friction estimates. Furthermore, because it uses transient data, it fits better the normal monitoring of the system. Another advantage is to provide the quick location of sudden ruptures by the analysis of the sharp transient event induced on the system.

Considering the problem involves the calculation of the roots of an equation, **Liggett & Chen (1994 & 1995)** have compared Newton-Raphson method with Levenberg-Marquardt to carry out the minimisation, concluding that the latter converges faster. The usual disadvantage of these methods is the gradient calculation. Other optimisation techniques, that do not involve derivatives calculation and that are trustworthier to find the optimal solution in a large search domain, can also be used. Genetic Algorithms is one global search method already applied to inverse transient analysis for leakage detection and roughness calibration (**Nash & Karney, 1999**; **Vitkovsky *et al.*, 2000b)**.

2.2 Motivation and missing issues

The inverse transient analysis has been conceptually elaborated and numerically verified with artificial data generated by a transient simulator (**Liggett & Chen, 1994, 1995**). However, there is no evidence, yet, in the literature, of field or laboratory testing of the methodology covering the following issues: (i) the assessment of the inverse transient methodology, concluding whether it is applicable and under which circumstances; (ii) the quantification of uncertainties associated to the parameters estimation procedure; (iii) the acquisition system synchronisation of the data measurements in real systems; (iv) an outline of a set of rules to define the sampling rate, the sample size and the location of the measurements sites; (v) an overview of practical difficulties of the implementation and success of this methodology.
The scope of this paper does not intend to cover all these issues focusing mainly on a preliminary assessment of the inverse transient analysis based on laboratory data collected in a looped system and attempting to forecast eventual difficulties of in the field implementation of the method. The other issues will be covered in future works.

2.3 Model development

2.3.1 Introduction

The investigated inverse transient methodology for leakage detection and network calibration was encoded to form a computer program. For this purpose, a transient solver and an inverse search engine were implemented using an object-oriented programming approach (**Figure 2**).

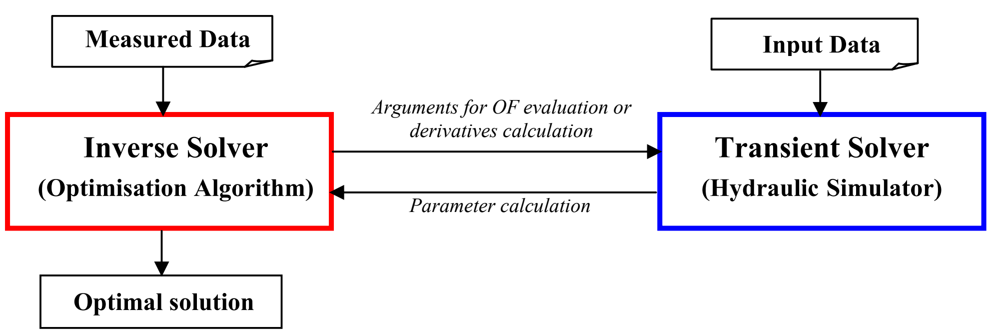

Figure 2 – Modules-interconnection in the Inverse Transient Tool

The Inverse Solver (IS) is the search engine that runs the optimisation procedure and attempts to find the best solution of the minimisation problem. On the other hand, the Transient Solver (TS) is the simulator of the hydraulic transient events, given certain boundary conditions. The TS is called by the IS either to evaluate the objective function (OF) or to calculate the derivatives. Although these modules are interconnected, they are independent since the TS can be run apart from the IS and the IS can call with any other hydraulic simulator.

2.3.2 Transient Solver

The implementation of the inverse transient method presupposes the development of an accurate and robust transient solver and a reliable optimisation algorithm. Although the transient solver implementation might not be considered an original contribution, its importance relies on the fact that the lack of accuracy on the simulation of the physical phenomenon of the hydraulic transient might result on the failure of the overall proposed inverse methodology.

Thus, a network transient solver was implemented using the typical method of characteristics to solve the partial differential equations, incorporating several boundary and internal conditions, such as reservoirs, valves, pressure dependent demands (leaks), and applying different approaches for steady and unsteady friction calculation. More details about general hydraulic transients modelling in pipe networks can be found in **Almeida & Koelle (1992)** and **Streeter & Wylie (1993)**.

In the current research, unsteady friction losses were modelled by the formulation presented by **Brunone *et al.* (1991a), (1995)** with improvements by **Vitkovsky *et al.* (2000a):**

$$f = f_s + \frac{k' DA}{Q^2}\left(\frac{\partial Q}{\partial t} + a \cdot \frac{|Q|}{Q} \cdot \left|\frac{\partial Q}{\partial x}\right|\right) \tag{1}$$

where f_s is the Darcy-Weisbach friction factor, k' is a "decay coefficient" which has to be calibrated to each situation based on collected data, Q is the flow, a is the wave speed, A is the pipe cross section, D is the pipe internal diameter, x is the coordinate axis along the pipeline and t is time. This formulation can be easily incorporated in the method of characteristics.

2.3.3 Inverse Solver

The Inverse transient analysis attempts to estimate unknown parameters using observed pressure or flow data, collected during the occurrence of transient events. The parameter identification is an optimisation problem in which the system's behaviour is simulated by a hydraulic model and the difference between observed and calculated variables is minimized by means of an optimisation model.

In the present case, observed data is composed of pressure measurements in several sites of the network. Generally, pressure data is easy to collect and the acquisition rate of pressure measurements can be extremely high which is important in transient events data collection. Several parameters can be estimated, however, in this particular case, the unknowns are only leaks locations. The inverse solver, as an optimisation algorithm, is driven by an objective function, which, in its simplest form, can be expressed by the sum of the quadratic errors between observed and calculated parameters, known as the ordinary least squares formulation:

$$\underset{\mathbf{p}}{\mathrm{Min}}\ \mathrm{OF}(\mathbf{p}) = [\mathbf{q}^* - \mathbf{q}(\mathbf{p})]^T [\mathbf{q}^* - \mathbf{q}(\mathbf{p})] \ = \ \sum_{i=1}^{M} (q^*_i - q_i(\mathbf{p}))^2 \qquad (2)$$

where OF(**p**) is objective function, **p** is parameter-vector with N decision variables, **q**(**p**) is predicted system's response vector (with M elements) for a given parameter vector **p**, **q*** is the observation-vector (with M elements), whose elements are measured heads, M is the number of measurements. Nevertheless, different types of objective functions can be implemented which will definitively influence the convergence speed and lead to more accurate estimates of the parameters.

Furthermore, different optimisation techniques can be used. Hence, two main optimisation algorithms based on gradient methods and heuristic techniques were implemented in the current Inverse Solver, namely Levenberg-Maquardt method and Genetic Algorithms. However, there is no guaranty that any of the implemented optimisation methods will find the global optimal solution, not being stuck in a local extreme. Moreover, because Genetic Algorithms are based on random search, they are extremely time-consuming compared to the gradient methods: for a convex objective function, while a Newton method may converge in 10 iterations, the Genetic Algorithm method may require 1000 evaluations of the same function.

The inverse transient algorithm starts with the generation of an initial solution which can be carried out randomly, attributing values to the parameters within a certain predefined range (typical Genetic Algorithms procedure) or deterministically, initialising the parameters based on the engineer initial guess (usually used in gradient methods). The next step is the objective function evaluation. For this propose, the TS is called by the IS, to solve the hydraulic system and calculate the pressure in the measurement sites. According to the value of the OF and the defined termination criteria, a new solution is generated. In case termination criteria are not verified, a new solution is generated. This new generation usually needs to call the TS either to calculate the derivatives or to evaluate a population of random solutions. Given this newly generated solution, the objective function is evaluated again and the process repeats until termination criteria are verified and the optimal solution is found.

3 EXPERIMENTAL DATA

3.1 Description of Experimental Set-up

An experimental facility with a looped system was assembled at the Laboratory of Hydraulics of Civil Engineering Department of Instituto Superior Técnico (Technical University of Lisbon). This facility was specially designed for leakage detection purposes with a two-fold goal: (i) firstly, to collect leakage transient data to put into a transient database (Transdat) developed in the scope of a EU Project SMT4-CT97-2188; (ii) secondly, to test and analyse the inverse transient leakage detection methodology.

The configuration of the experimental set-up consists of a pipe network with six square loops, having each loop 2m×2m, supplied by a pressurised vessel with a constant pressure around 26m (**Figure 3**). The pipes are massively anchored in several sites along its length, in order to avoid any longitudinal movement in the several fittings of the system (elbows, tees or valves) during the transient event. The pipes are made of transparent PVC PN10 (nominal pressure 10 $kg.m^{-2}$), with 45 mm internal diameter and 2.4 mm of wall thickness.

At the downstream end of the network, there are two valves: a gate valve, to control the flow, that discharge to the atmosphere and a ball valve, immediately upstream the former, to generate the transient event. The closure of the water-hammer valve is carried out manually.

The leaks are located at interior sections of the hydraulic system and are simulated by small ball valves with 9 mm of inner diameter discharging directly to the atmosphere.

The data acquisition system is composed of an acquisition board (Spider 8, from HBM) with eight analogue inputs channels to connect measurement equipment and with one output parallel port, eight gauge transducers (HBM) and a notebook computer. The sampling rate of the data acquisition system board is 100 kHz. Pressure transducers are of strain gauge type, with a range of –1 to 9 $kg.m^{-2}$, with an accuracy of 0.5%, located in several sites of the system (**Figure 3**). Pressure measurements were carried out in six measurement sites.

An electromagnetic flow meter, located at the upstream end after the pressurised vessel, is used to measure steady state flow.

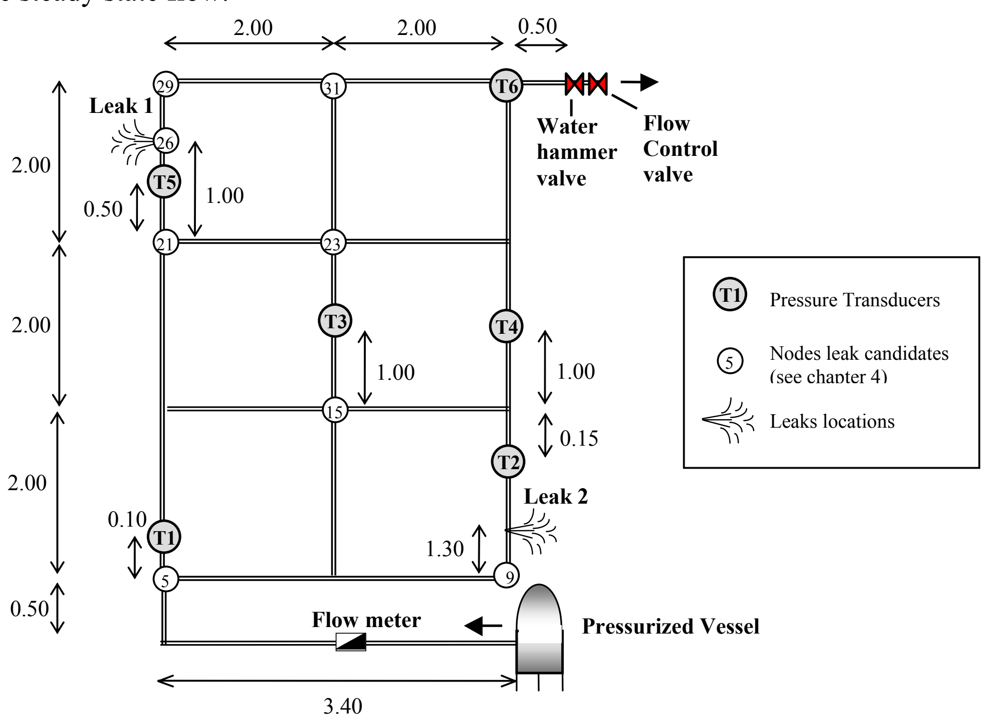

Figure 3 - Configuration of the experimental facility at Instituto Superior Técnico

3.2 Data Collection

Several experimental tests were carried out in the network without leakage and with several leaks locations and sizes. In this paper, only two tests will be presented (Table 1): the first one corresponds to the system without leakage – "No Leak" test – and the other one with a leak located at node 26 and with the size of 0.00003 m^2 – "Leak 1" test. For these tests, the initial steady state flow at the downstream end is 1 l/s. The hydraulic transients were generated by the closure of the downstream water hammer valve.

Figure 4 presents the collected pressure data at the six transducers (T1 to T6) in the "No Leak" test and in the "Leak 1" test. The sampling rate has been 600 Hz and the data collect during 10 s. Nevertheless, only part of the collected sample will be used in the inverse analysis since after a couple of periods of the pressure wave most transient solvers show a certain uncertainty in the calculated results. **Figure 4** only presents the collected pressure until 1s.

Comparing these two tests (**Figure 4**), an important phase shift of the pressure wave can be observed at all measurement sites in the "No Leak" situation. This reflects the effect of unsteady friction losses in the system without leakage, effect that increases its importance with time.

This phenomenon is not so evident in the "Leak 1" test. The reasons for this are: first of all, there is no accurate reference pressure wave to compare the "Leak 1" test, in order to assess the change of this oscillatory pattern; secondly, given the presence and the size of the leak (the initial leak flow is around 1/3 of total flow at upstream), the transient event is damped much more rapidly than in the system where the leak does not exist, consequently minimising the phase shift effect. Furthermore, the pressure wave damping in the "Leak 1" test is assured by the leak itself that behaves similarly to a relief valve, dissipating almost immediately the transient event.

Thus, the unsteady friction effect was neglected for the inverse analysis of referred leak situation; however, this effect should be considered in the "No Leak" situation, having the decay coefficient to be adjusted to each particular case and simulation period.

Table 1 – Experimental Tests

Test	Initial flow at downstream	Initial leak flow	Leak's effective size (*)
"No Leak"	1 l/s	-	
"Leak 1"	1 l/s	0.670 l/s	0.00003 m^2

(*) Leak's effective size is $A_{ef}=C_D.A_L$ where C_D and A_L stand for the discharge coefficient and the area of the orifice.

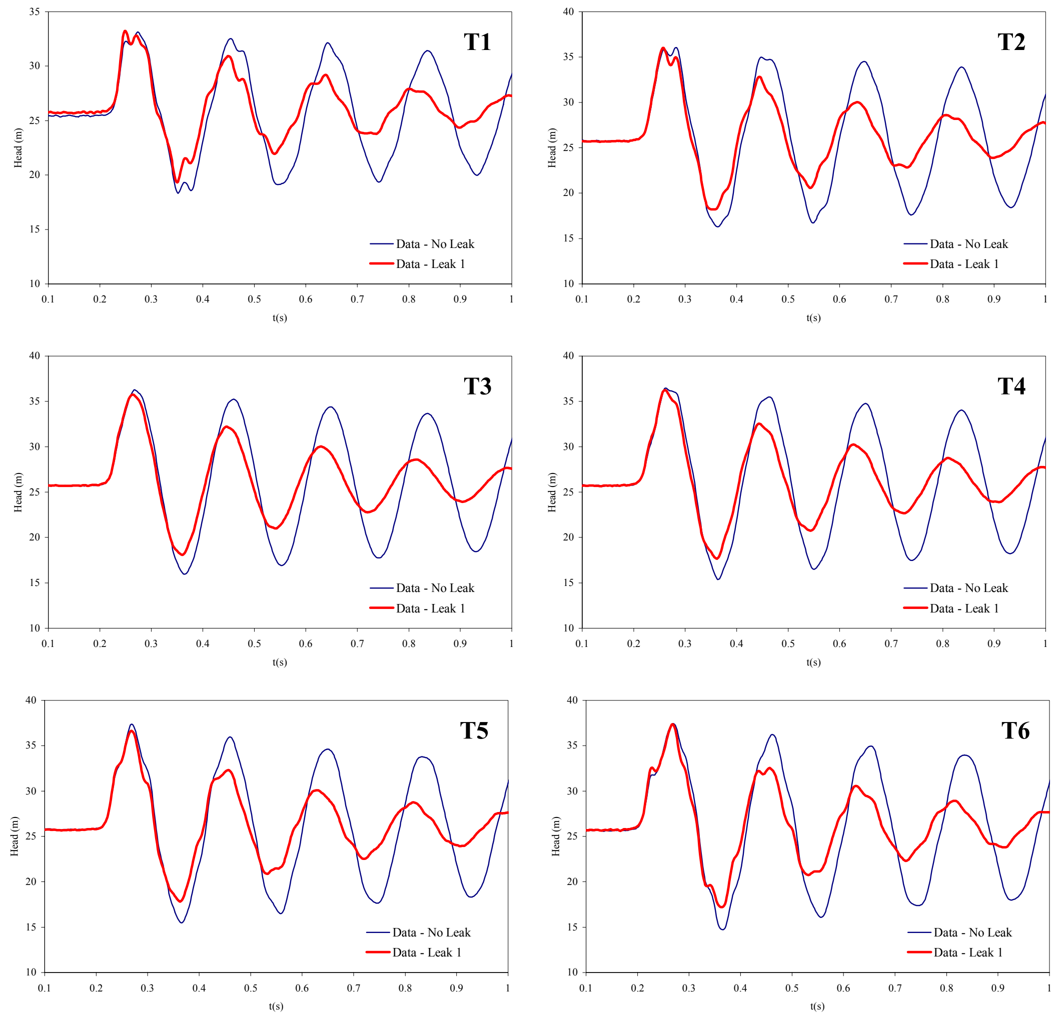

Figure 4 – Transient pressure data in "No Leak" test versus "Leak 1" test at six measurement sites

3.3 Parameter Calibration

The steady-state data, in terms of flow and pressure, allows the estimation of pipe friction roughness k used to evaluate the steady-state friction factor f_s in the Colebrook-White formula. The estimated pipe roughness, including local head-losses, was approximately 0.0001 m.

In single systems, wave velocity can be estimated by frequency analysis of the pressure response at the downstream end of the pipe. However, in this particular case, since the system is a looped pipeline, the former procedure is not applicable, neither is any theoretical expression accurate enough to calculate it, since the pipeline is anchored against longitudinal movement in several sections along its length. Thus, the wave velocity had to be adjusted by computer simulation, in trial and error procedure. Since for the "Leak 1" test the phase shift due to unsteady friction is insignificant, the decay coefficient was assumed to be null and the adjusted wave speed was a=475 m/s. This value is higher than the expected due to system's constraints (conduit anchored with concrete massifs) in several sections.

Although the unsteady friction losses can be neglected (the decay coefficient has been considered zero) in the leaks situation, these have to be taken into account in the "No Leak" situation or for small leaks tests. In these circumstances, the decay coefficient varies with the size of the analysed sample: the longer the analysed sample size, the more significant is the phase shift and, therefore, the higher is the best-fit value of this coefficient.

3.4 Collected Data vs. Numerical Results

The transient response of the system was measured in the six pressure transducers. The head-time variation obtained experimentally in two transducers (T1 and T6) versus numerical results obtained by the transient simulator after the referred calibration is presented in **Figures 5** and **6**, for the two tests of Table 1.

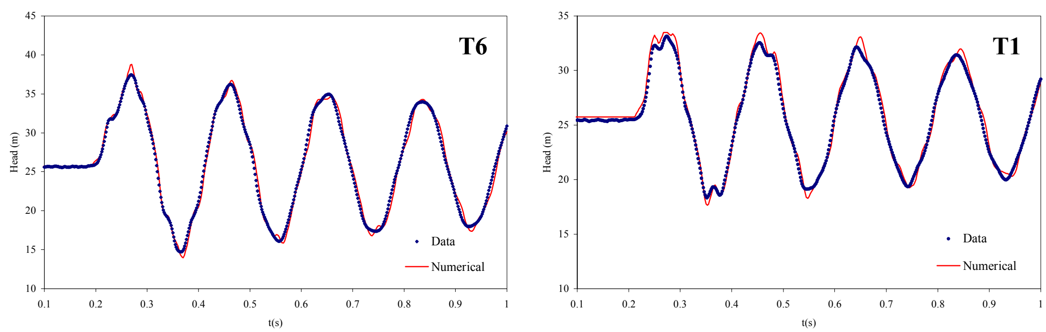

Figure 5 – Collected data versus calibrated numerical results for the "No leak" situation

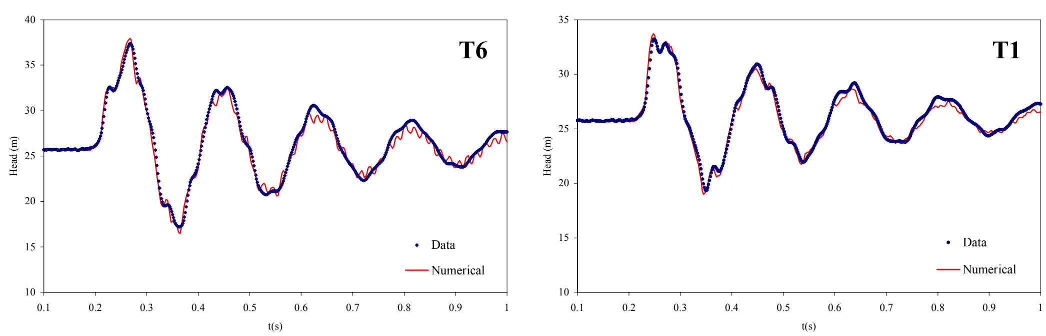

Figure 6 – Collected data versus calibrated numerical results for the "Leak 1" situation

The numerical results adjust fairly well to the experimental data in all measurement sections, which confirms the accuracy of the transient model in the simulation of slow transient events in complex systems. However, this good adjustment tends to degenerate after a few periods of the pressure wave. The reason is that the transient solver does not dissipate the residual frequencies, particularly when unsteady friction modelling is neglected (which is the case of the simulation of the "Leak 1" test). The residual frequency generated by the leak is a typical example of a frequency not dissipated by the numerical model (see **Figure 6**). Conversely, the

higher the frequency, the fastest its energy attenuation and the 1-D numerical models are still not capable of representing it accurately.
Furthermore, there are other sources of uncertainties in the numerical simulations. One is eventually the inaccurate flow distribution in the network due to local head losses in the elbows and tee-junctions, losses that are particularly important since the pipe's diameter is relatively large (45 mm) compared with the length of the pipes (2 m). These head losses have been included, though, in pipe roughness. The natural consequence of this inaccurate flow distribution in the leakage location procedure is that the inverse method will try to compensate artificially these disagreements pointing to leaks in the wrong location.

4 LEAKAGE DETECTION USING COLLECTED DATA

In order to test the developed inverse transient solver, an example of inverse leakage detection using Levenberg Maquardt optimisation method is presented herein. The inverse method was tested using the transient data collected in the six pressure transducers for the "Leak 1" test. An initial solution without leakage has been considered to start up the iteration process.

4.1 Sparse leak candidates

At a first stage of the inverse analysis, five nodes - nodes 5, 9, 15, 23 and 29 - were considered potential candidates to leaks locations (see **Figure 3**). None of these corresponds to the true leak position. This would be the normal procedure in a field network: in a preliminary stage, leaks locations would be assumed in several sites spread all over the system, in order to assess the network area more susceptible to have leakage; afterwards, based on the results, the area with leakage would be refined with more leak candidate nodes.

Only part of the collected data in the six pressure transducers was used in this inverse analysis - a sample size of 1.2 s. The several solutions obtained in the Levenberg Maquardt convergence process are presented in **Figure 7(a)** and the final solution versus the collected data is presented in **Figure 7(b)**.
Ideally, the objective function should be zero since the minimum would correspond to no difference between the data and the results. However, neither the data nor the numerical results are perfect, therefore the global minimum of the optimisation problem when using laboratory or field data is not zero. In the current case, the best solution found has a minimum of the objective function equal to 397 (see **Figure 7(a)**).
As it can be observed in the **Figure 7(a)**, the Levenberg Maquardt convergence is very fast which is typical of gradient methods. Furthermore, the inverse method pointed to a presence of a leak in the neighbourhood of nodes 23 and 29, which is correct since the leak is located at node 26. However, it pointed, as well, to a leak at node 5. This may be due to the slight disagreement between the data and the simulation results that the optimisation algorithm tries to compensate with a leak in the wrong location (at node 5). Finally, the sum of the estimated leaks sizes is exactly the size of the true leak $3\times10^{-5}m^2$, although distributed by three different nodes - 1×10^{-5} m^2 in node 5, 0.5×10^{-5} m^2 in node 23 and 1.5×10^{-5} m^2 in node 29. The highest estimated leak size (at node 29) is exactly the node closest to the leak true location (node 26).

Figure 7(b) shows a good agreement between the best solution found and the data, with the exception of transducer T1.

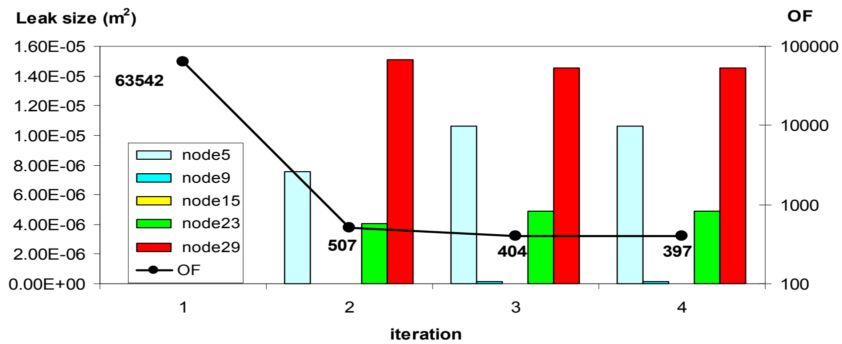

Figure 7(a) – Convergence for a simulation time of 1.2 s (candidate leak nodes 5, 9,15, 23, 29)

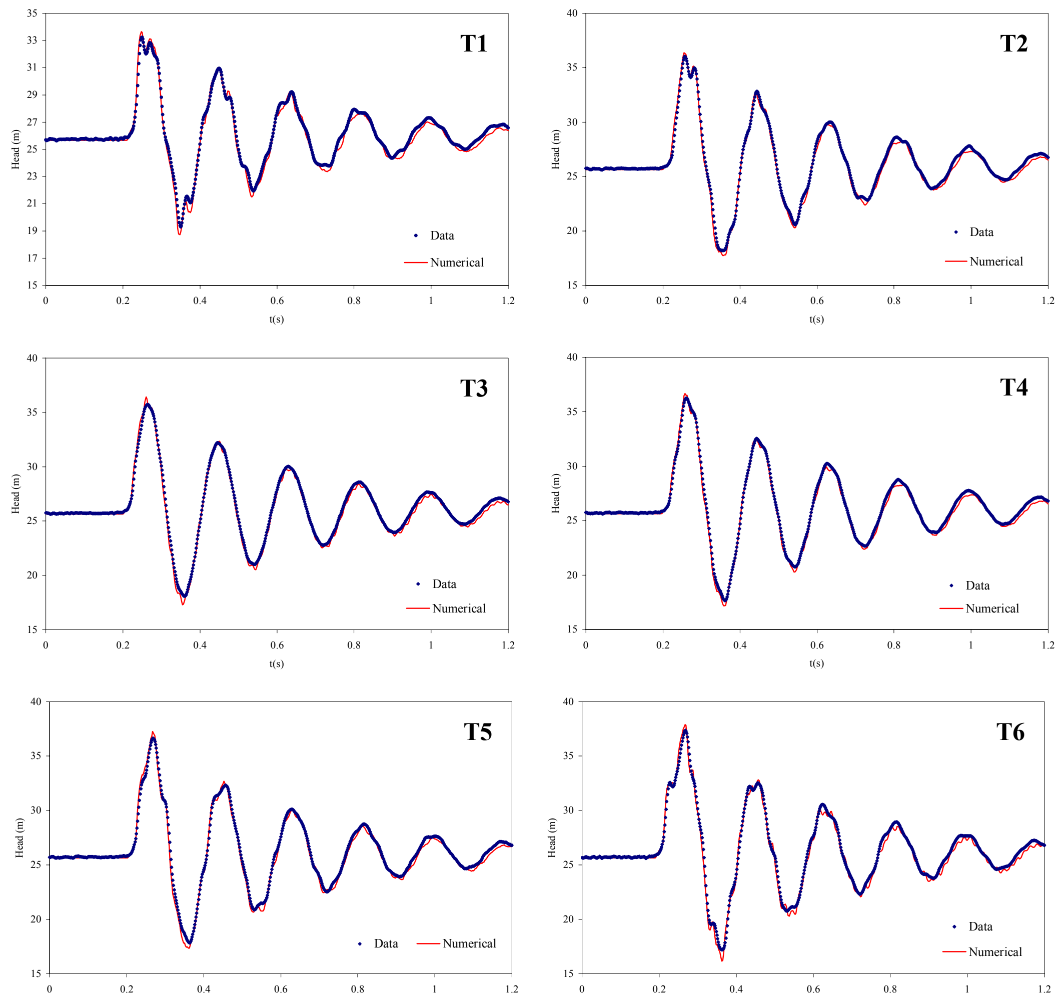

Figure 7(b) - Collected data versus numerical results of the best fitted solution for the "Leak 1" test

4.2 Refined leaks candidates

The preliminary inverse transient analysis presented in the previous section, although not conclusive, allowed having an idea of the area of the network where the leak (or rupture) is more likely to be located – near nodes 23 and 29. Thus, a second run was carried out adding three more nodes to the list of potential leaks. Eight nodes were assumed as potential candidates to leaks locations - nodes 5, 9, 15, 21, 23, 26, 29 and 31 (see **Figure 3**).

The correct location of the leak is at node 26 and with an effective leak area $A_L=3x10^{-5}$ m^2. This node was chosen intentionally as a leak candidate to assess the capability of the model of detecting it and estimating accurately its magnitude. Several sample sizes (simulation periods) have been considered in the inverse analysis, however only three (0.8 s, 1 s and 1.2 s) are presented herein – **Figures 8, 9** and **10**.

When the analysis was carried out for simulations times higher than 1.2 s (**Figures 10**), the leak was not located correctly, since the residual frequency generated by the leak, dissipated in the real system, becomes more important in the numerical results as the transient pressure is damped. Since this uncertainty does not appear in the collected data, thus the inverse algorithm tried to compensate it with a completely wrong leak location.

Conversely, for simulations times of 0.8 s and 1.0 s used in the inverse analysis (**Figures 8** and **9**), the method pointed to the correct position of the leak (node 26), although with some uncertainty concerning its size: the estimated leak size was almost half of the true value. Moreover, the method pointed equally to small leaks located near the true leak position as well as at nodes 5 and 9. The firsts seem to be normal given the approximations of the transient solver. The last two are, once more, due to the slight disagreement between the data and the numerical results obtained by the transient solver. The only numerical way that the optimisation method has found to reproduce this behaviour was to allocate false leaks at these nodes. These false leaks can be easily distinguished from the true ones by their small size ($0.6x10^{-5}$ m^2).

The transient event was generated by a slow closure manoeuvre of valve: the total estimated closure time is around 0.08 s compared to the elastic reflection time (2L/c) which is 0.06 s. Hence, the simulation time to carry out the inverse analysis that leads to the best results was 0.8-1.0s that correspond, respectively, to 3 and 4 periods of the pressure wave. On the other hand, if a fast manoeuvre had been performed, the analysis would have to be carried out only in the first or second transient pressure wave, because after that, the transient simulator would not be able to reproduce accurately the transient event.

Theoretically, the longer the size of the measured data, the faster and more accurate would be the convergence (**Vitkovsky *et al.*, 2000b**). However, and as it has been shown with the experimental data, the transient solver does not simulate perfectly the measured hydraulic transient mainly due to unsteady friction; this inaccuracy increases with time. Thus, what has been verified was the opposite, the smaller the sample size within a certain minimum limit, the more successful is the method and the more accurate is the solution found.

The question is how to define the optimal simulation time (or the optimal sample size) to carry out the analysis. The question is still unsolved and it may depend on the topology of the system and the accuracy of the estimated parameters (wave speed, roughness, type of valve manoeuvre). Though, when the inverse transient method is applied to detect leaks or to estimate any other parameter, it is strongly recommended the analysis of several simulation times (or sample sizes) in order to compare the results and assess which one produces the best and the most accurate estimated of leaks locations. Furthermore, when a leak is found completely isolated on a certain area, this estimate of the leak location should be considered with some reservations. Conversely, if the leak appears with other leaks nearby, then, this is an indication that something wrong is happening in that area and a more detailed analysis should be carried out.

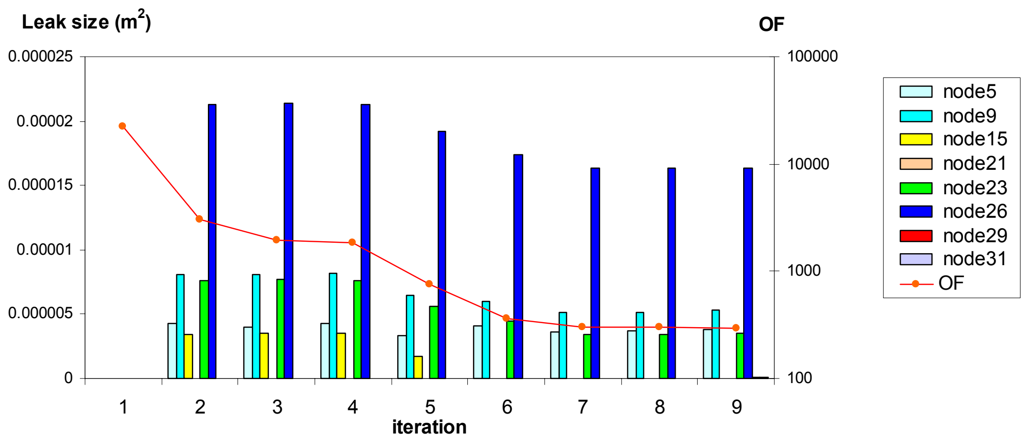

Figure 8 – Convergence for the sample sizes 0.8 s (candidate leak nodes 5, 9, 15, 21, 23, 26, 29, 31)

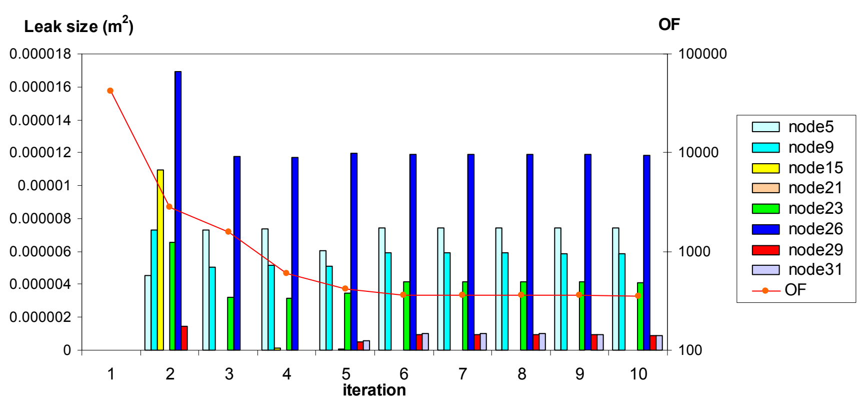

Figure 9 – Convergence for the sample size 1.0 s (candidate leak nodes 5, 9, 15, 21, 23, 26, 29, 31)

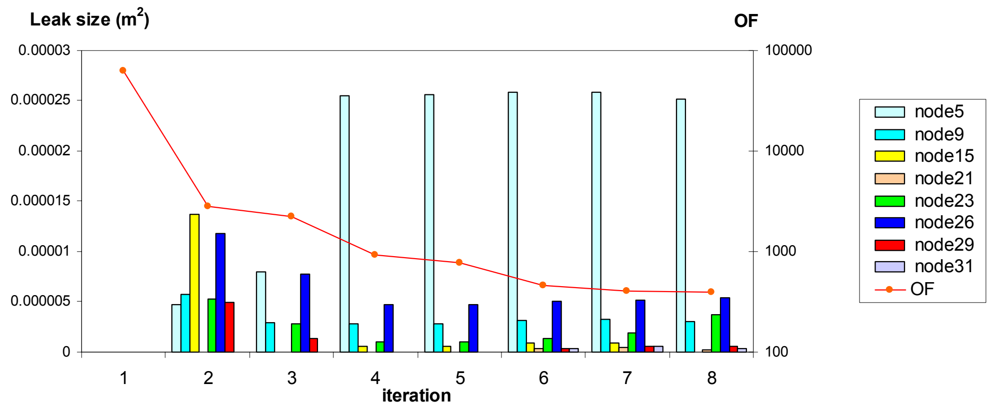

Figure 10 – Convergence for the sample size 1.2 s (candidate leak nodes 5, 9, 15, 21, 23, 26, 29, 31)

5 FINAL REMARKS

The inverse transient methodology was presented conceptually and implemented in a software tool. The efficiency of the method was shown with an example based on laboratory tests of leakage transient data. The method was well succeeded to detect leaks although, in the presented case, the leak flow was around one third of total flow at the inlet of the system. The method still has to be tested for smaller leaks to assess the minimum detectable leak by this method. However, it should be emphasised that given all sources of uncertainties both on the data and on the transient results, the method might not able to locate accurately small leaks.

The analysis carried out has shown that the existing 1-D transient solvers, even when unsteady friction modelling is taken into account, are still not accurate enough to simulate both fast and slow transients a couple of pressure waves after the transient has been generated. Therefore, the accuracy and success of the inverse method depends strongly on the period in which the analysis is carried out. Thus, the sensitivity analysis of the simulation time is recommended in each particular case, in order to have more confidence on the results.

Although the inverse transient method seems relatively simple to apply in water networks, its efficiency relies on several factors: (i) the accuracy of the transient simulator to reproducing the behaviour of the system, (ii) the uncertainty of collected data, (iii) measurements synchronisation in respect to time and to datum level, (iv) the accuracy of the estimation of the main water hammer parameters, such wave speed, pipe roughness and closure manoeuvre that generated the transient.

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